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# Eyeburn Thresholds

by

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ABSTRACT

This report describes a series of calculations that relate to identification of minimum threshold conditions for production of retinal burns, such as may occur in the imaging of intense light sources; e.g., lasers and nuclear explosions. These calculations consider the combined effects of optical absorption and thermal conduction in the retinal tissue for image diameters ranging from 1 to 1000 microns. Threshold energy dose levels are computed, based on the assumption that a retinal burn is the result of a temporary temperature excursion of at least 20°C. The results are compared with laboratory measurements of eyeburn threshold levels in primates and rabbits. A set of computed "safe" retinal dosage curves is presented, based on the assumption that temperature excursions of 5°C or less are not harmful, (5°C being the expected maximum temperature rise produced in an image of the sun).

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## I. INTRODUCTION

Our ability to make eyeburn safe-distance predictions for nuclear tests has been hampered heretofore by the fact that reliable eyeburn threshold dose data were not available for image sizes below 100 μ. The present report is directed toward resolution of this problem. A series of calculated threshold dose levels is presented, based on a physical model which fits existing laboratory data, and which we propose to use for extrapolation of the data to smaller image sizes.

The accepted physical model of an eyeburn situation is that an image of the intense source is formed on the 10-μ thick pigmented epithelium (P.E.), which has a known, wavelength-dependent optical extinction coefficient. A fair fraction of the incident energy is absorbed in the P.E. Of the portion which is transmitted, another fraction is absorbed in the lighter, 100-μ thick choroid behind the P.E. As optical and infrared energy is absorbed, the temperature tends to rise while some of the heat is conducted away. If the temperature excursion is large enough (≥ 20°C), a burn results. The mathematical formulation of this model is described in the Appendix.

Two-dimensional numerical computations based on the above model, have been reported previously;[1,2,3,4] however, the results were not put to use in extending the range of the eyeburn threshold data. We have found it advisable to repeat and extend the calculations of Refs. 1, 2, and 3 although we have shortcircuited most of the computing by an analytic solution described in the Appendix. Our calculations are in substantial agreement. There are some relatively minor differences that we attribute to finite-mesh errors in the published numerical computations.

## II. CALCULATIONS AND COMPARISIONS WITH DATA

For these calculations we assume that the thermal properties of the retinal media are the same as those of water; i.e., thermal conductivity k = .0015 cal $cm^{-1} sec^{-1}$ $°C^{-1}$, density 1 g $cm^{-3}$, and specific heat 1 cal $g^{-1} °C^{-1}$. A circular image with a known spectral distribution, and with a fixed radius a and uniform intensity $I_0$ cal/$cm^2$sec, is formed on the retina at time zero, and maintained constant for a time Δt. We calculate the energy $Q = I_0 \Delta t$ required to produce a specified temperature increase one micron behind the front surface of the P.E., as a function of the image radius a and the impulse duration Δt. These assumptions are identical to those of Mainster et al.,[1] and the results are compared in Fig. 1 for the case of a monochromatic 7000 Å light source.

A large body of laboratory measurements of retinal burn threshold dosages in rabbits has been collected by the Medical College of Virginia,[4] the USAF School of Aerospace Medicine[3] and by Technology Incorporated of San Antonio, Texas.[5] More recently, the experiments have been extended to primates and the results reported by Miller and White.[3] Both extramacular and foveal burn thresholds have been determined.

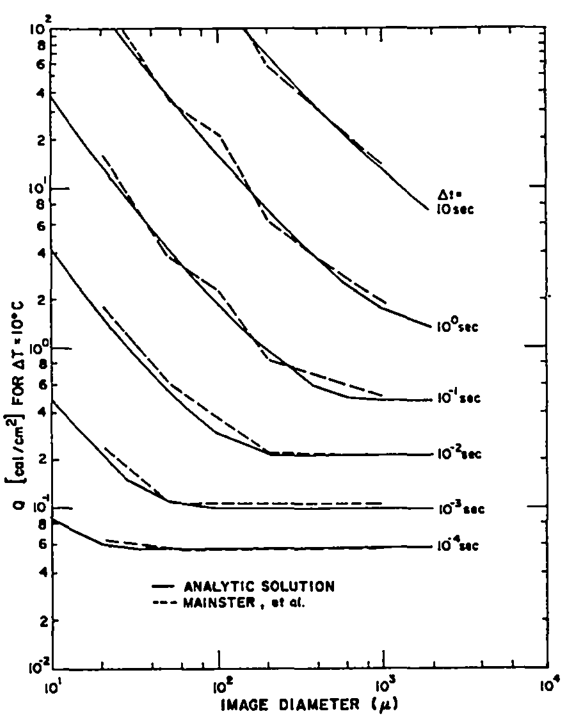


Fig. 1. Comparison of the analytic solutions to the numerical solutions of Mainster et al.[1] for various values of $R_0$ and t. Monochromatic 7000-Å source.

We have performed three separate sets of retinal heating calculations. The first set is intended to represent, as closely as possible, the experiments conducted with primates. Some of the input conditions are plotted in Fig. 2. Figure 2a is the spectrum of the light source used in the experiments, a Zeiss photocoagulator.[3] Figure 2b is a plot of the assumed values of spectral extinction coefficient of the P.E. and choroid, which were used in the calculations. These values were derived from the recent measurements by Geeraets and Berry[6] including corrections for reflection and scattering, with the auxiliary assumptions that; 1, in primates (rhesus monkeys) the extinction coefficients of P.E. and choroid are equal[7] and 2, the P.E. and choroid are 10 and 100 μ thick, respectively. Figure 2c is a plot of the primate anterior ocular media, from Geeraets et al.[6,8]

The calculated results for primate parameters are plotted in Fig. 3, in terms of the retinal exposure, Q, in calories per square centimeter incident on the P.E., required to produce a transient 20°C temperature rise one micron behind the front surface of the P.E. Q is plotted as a function of the geometric image diameter for various values of the exposure duration Δt. The spectral distribution of Q is that of the Zeiss photocoagulator, modified by the absorption that occurs in the anterior ocular media.

The experimental data for primates are also plotted in Fig. 3, and are found to lie very close to the corresponding theoretical 20°C temperature rise curves. From this fact, we are encouraged to conclude that; 1, the model represents a reasonably close approximation to the experimental situation, and 2, that a momentary 20°C temperature excursion constitutes a sufficient condition for expectation of an observable burn.*

The rabbit threshold data and the corresponding calculations are plotted in Fig. 4. In this case the agreement is not nearly as good. The calculated curves, as before, represent the values of Q necessary to produce a 20°C temperature rise. For these calculations we have taken $\alpha_1$, the extinction coefficient of the P.E., to be approximately five-times larger than $\alpha_2$, the extinction coefficient of the choroid.** The values used for $\alpha_1$ and $\alpha_2$ are plotted in Fig. 5, along with the transmission coefficient of the anterior ocular media. The rabbit data[5] are based on ophthalmoscopic observations performed 5 min after the exposure, rather than 5 h, as was the case with the primate data. The points plotted in Fig. 4 have been adjusted downward by a constant factor 0.75 to make them more nearly comparable to 5-h data.*** The rabbit data include image diameters extending down to 55 μ. It is generally agreed that threshold burns smaller than 100 μ are very difficult to detect, and this detection problem may contribute to the exceptional lack of agreement between the 55-μ data points and the experimental curves. Optical aberrations (chromatic aberration, diffraction, scattering, etc.) are not included in the calculations shown in either Figs. 3 or 4.†

Our intent in performing these calculations is to provide a physically sound method of extrapolation of the eyeburn threshold data to image sizes considerably smaller than 100 μ, since threshold values for very small images are needed for nuclear eyeburn safety studies. Because of the agreement between the calculations and the data, as shown in Figs. 3 and 4, we believe that the extrapolations can be made on the basis of the present heat flow model, modified in the 1- to 100-μ image diameter range by the inclusion of optical aberrations. In addition to the data and calculations, Fig. 4 contains the smoothed and extrapolated rabbit threshold curves taken from Allen et al.[9] We feel that the extrapolations indicated by these curves are not consistent with a plausible heat flow model or with any reasonable assumptions about the effects of optical aberrations.††

## III. SAFE RETINAL DOSE LEVELS

In order to estimate <u>safe</u> retinal dose levels for human beings, we proceed as follows:

Since a 20°C temperature rise seems to be sufficient to produce a retinal burn, a safe dose must certainly be one that does not produce a 20°C rise. We need also to allow for individual variations in retinal pigmentation, which can easily amount to factor-of-two variations in $\alpha_1$ and $\alpha_2$. We believe, with others,††† that a safe dosage

*Other experimental data and calculations, reported by Clarke et al.,[4] involved exposure durations of several minutes. It was found in that case that a 10°C temperature rise was sufficient to cause a burn.

**In rabbits, as in humans, the P.E. is considerably darker than the choroid. Following the suggestion of Dr. W. Geeraets,[7] we assume that the energies absorbed in each of the two layers are equal, and that the thicknesses of the P.E. and choroid are 10 and 100 μ respectively. These assumptions, combined with the data of Ref. 6, lead to the values of $\alpha_1$ and $\alpha_2$ plotted in Fig. 5. These values are not greatly different from those used by Mainster et al.[2]

***Experiments reported by Miller and White[3] indicate that threshold Q values obtained on the basis of a 5-min burn criterion are roughly one third higher than those obtained using a 5-h criterion.

†In normal vision, the human eye appears to be capable of focusing the image of a point source into a spot about 10 μ in diameter. It is, of course, possible for large image blurring effects to appear in the threshold experiments if the test animal does not have its eye focused accurately on the optical source. It seems likely that the exceptionally large measured values of threshold Q for image diameters of 100 μ and below may be due to experimental difficulties in focusing the source to an accuracy of better than 50 μ.

††However, see above footnote (†).

†††This opinion was originally expressed to us by Thomas J. White of Technology Inc.

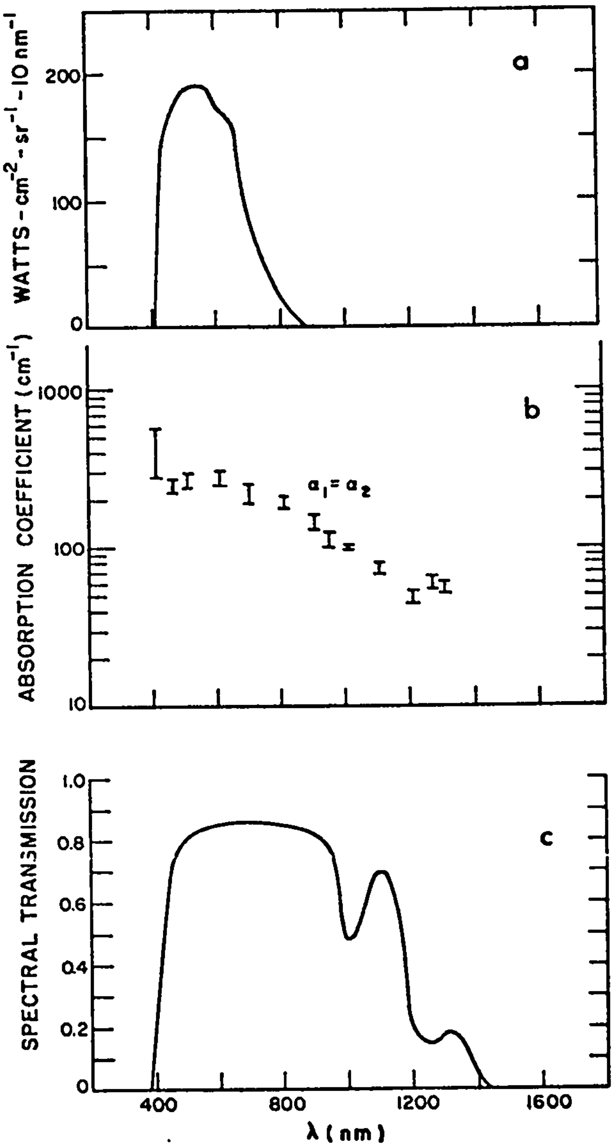


Fig. 2a. Spectral radiance of photocoagulator source;[3]
2b. Extinction coefficients of primate P.E. ($\alpha_1$) and choroid ($\alpha_2$), from Geeraets and Berry,[6] with the assumption $\alpha_1 = \alpha_2$;
2c. Transmission of primate anterior ocular media.[6]

level, $Q_S$, can reasonably be defined as one that produces a 5°C temperature rise in the P.E. of a nominal "average" individual. This is close to the temperature rise that is experienced in looking at the sun.

Values of the extinction coefficients $\alpha_1$, $\alpha_2$, and the eye transmission for the nominal average individual are plotted in Fig. 6. They are derived from the data of

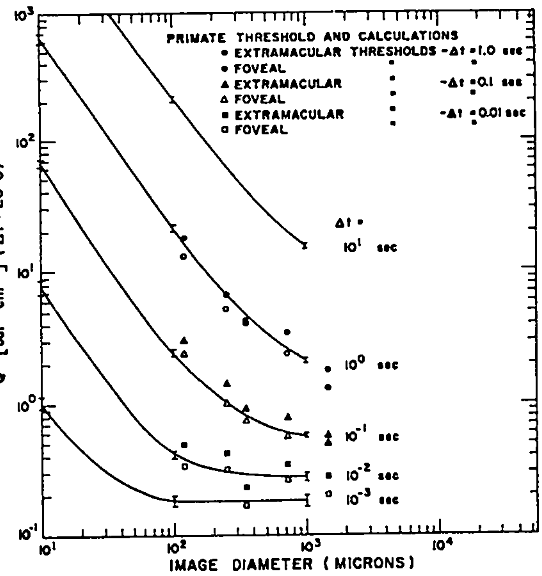


Fig. 3. Comparison of experimental foveal and extramacular threshold data for primates (Miller and White[3]) with calculations of energy dose required to produce a 20°C temperature rise. Error bars indicate uncertainty in calculated Q associated with uncertainty in $\alpha_1$ and $\alpha_2$.

Geeraets and Berry.[6]

The calculated retinal dosages for production of a 5°C temperature rise in the P.E. of the average (human) individual are plotted in Fig. 7. The spectrum assumed is that of a 5000°K blackbody, as transmitted through the anterior ocular media. The solid curves are the results of the calculations with no allowance for optical aberrations. The dotted curves include an estimated correction for aberrations.

The effect of aberrations is to redistribute the optical energy over an area larger than that of the geometric image. As an approximation, we assume that, for a normal eye and a "white" image, the blurring simply increases the effective image diameter by 10 μ, while the energy distribution remains uniform. Thus, to find the "corrected" values of $Q_S$, we translate each point on the solid curves for which the diameter, d, is greater than 10 μ to the left by an amount $\Delta d = 10$ μ, and then upward by the ratio $d^2/(d-10)^2$. One could properly argue about

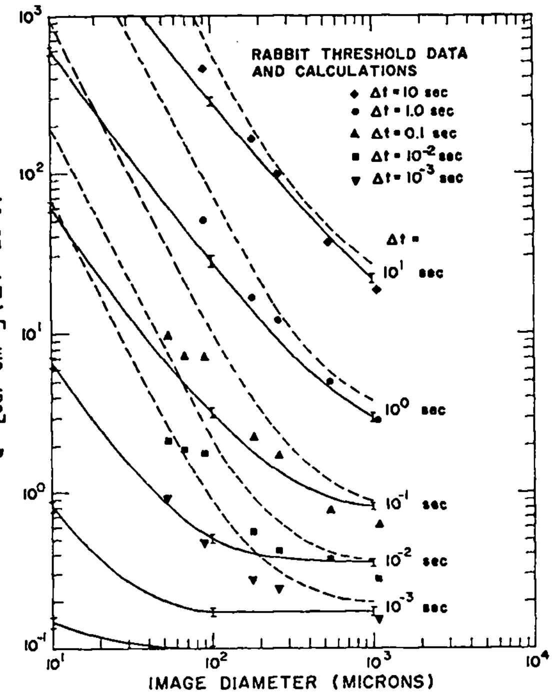


Fig. 4. Comparison of rabbit threshold data (Allen et al.[5]) with calculations of energy dose required to produce a 20°C temperature rise. Error bars associated with uncertainty in $\alpha_1$ and $\alpha_2$. Dotted curves are smoothed and extrapolated data curves from Allen et al.[9]

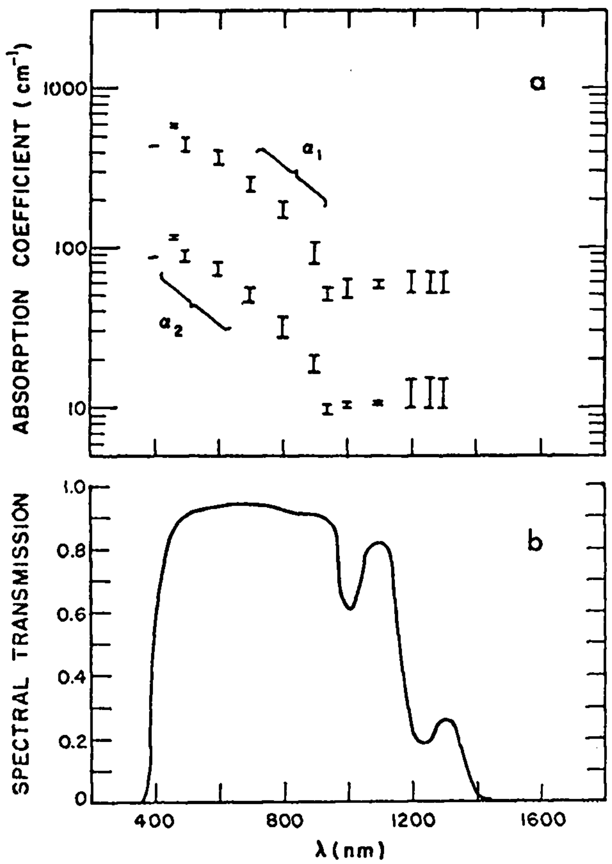


Fig. 5a. Extinction coefficients of P.E. ($\alpha_1$) and choroid ($\alpha_2$) in rabbit eyes, from Geeraets and Berry,[6] with the assumption that equal amounts of energy are absorbed in each of the two layers;

5b. Transmission of the rabbit anterior ocular media.[6]

the details of this model, but we claim that it is qualitatively right, and that our correction factor is accurate for most purposes to within a factor of three. Some experimental measurements of modulation transfer functions for the human eye have been made,[10,11,12,13] but their detailed interpretation is difficult. They nevertheless support the spirit of our assumption, that each point in the image is blurred over about 10 μ.

Figure 8 includes three sets of safe-dosage curves with the blurring correction included, equivalent to the dotted curves in Fig. 7, but with three different spectral distributions of the optical flux. The three distributions are those of a 5000, 10,000, and 15,000°K blackbody, each modified by transmission of the anterior ocular media. The conclusion to be drawn is that the safe dosage levels are not especially sensitive to the temperature of the radiating source, at least over the range 5000 to 15,000°K.

Figure 8 is, in a sense, the end product of this report. It includes our recommended values of safe retinal dosage for geometric image diameters between 1 μ and 1 mm, exposure durations between 100 μsec* and 10 sec, and for three blackbody spectral distributions.

## IV. RETINAL BURN HAZARD FROM NUCLEAR EXPLOSIONS

The intended application of these thresholds is in eyeburn hazard evaluation for

*For exposure times shorter than 100 μsec, please use Fig. 7. The 1 and 10 μsec curves are omitted from Fig. 8 for artistic reasons.

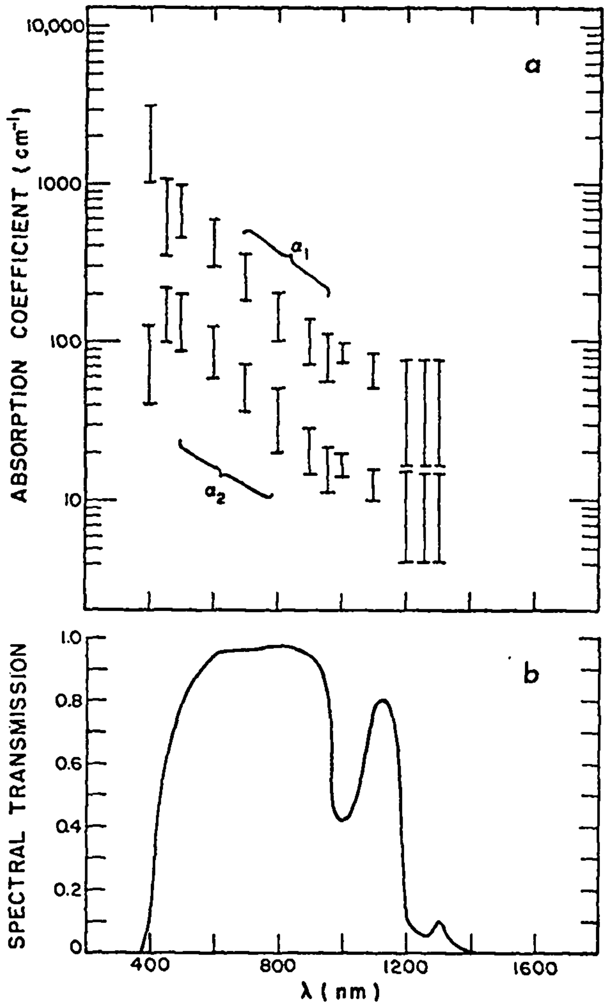


Fig. 6a. Extinction coefficients of P.E. ($\alpha_1$) and choroid ($\alpha_2$) in human eyes, from Geeraets and Berry,[6] with the assumption that equal amounts of energy are absorbed in each of the two layers;

6b. Transmission of the human anterior ocular media.

nuclear test exercises. It is of course true that the retinal exposure from a nuclear explosion is not uniform over the image, nor is the dose rate uniform in time. Some rather subjective judgments need to be made, therefore, when these thresholds are used. An example of their possible application is described below.

In any nuclear explosion, a fraction $f_{th}$ of the total yield Y is emitted as "prompt" thermal radiation, within a time $\tau$. Let us suppose that it is possible to define a single value for an effective source radi-

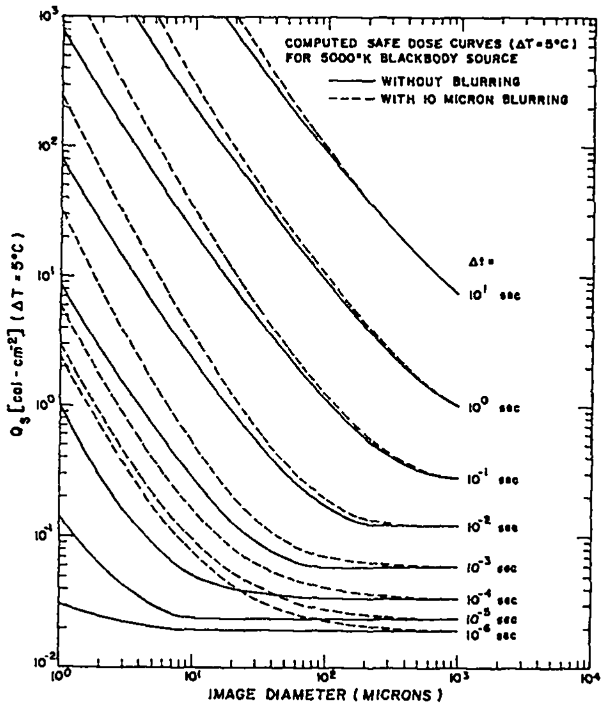


Fig. 7. Calculated "safe" dosage values, $Q_S$, for irradiation by a 5000°K blackbody source. $Q_S$ is the value of Q calculated to produce a 5°C temperature rise in the P.E. of the nominal "average" human. The dotted curves include estimates of optical blurring effects (see text).

us, $R_{fb}$, for this thermal radiation. Suppose an observer is at a distance D from the explosion, and the effective optical transmission of the intervening air is $T_{air}$. Suppose further that the observer's pupil aperture is $A_p$, and his eye has a focal length F and transmission $T_{eye}$. Then the energy absorbed per square centimeter in the geometric image on the observer's retina is

$$Q = \frac{f_{th}\ Y\ A_p\ T_{air}\ T_{eye}}{4\pi^2\ R_{fb}^2\ F^2}$$

ignoring optical aberrations. The distance, D, enters only through its effect on the air transmission $T_{air}$. The diameter of the geometric image is

$$d = 2R_{fb}\ F/D\ .$$

Upon having computed Q and d for a given situation, one may enter Fig. 8 with d, and with the given value of the thermal pulse time $\tau$, to find the corresponding safe dose

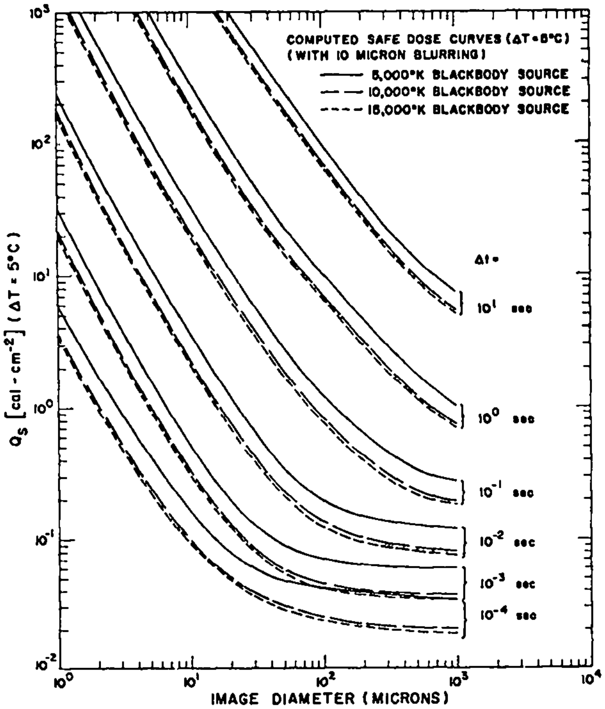


Fig. 8. Calculated safe dosage values, $Q_S$, for 5000, 10,000, and 15,000°K blackbody sources. Optical blurring effects included.

value $Q_S$. The observer should not receive a retinal burn if Q is found to be smaller than $Q_S$.


ACKNOWLEDGMENTS

Most of the physical ideas in this report were not originated by us. Some came from the literature, and some were derived from private discussions. Our motivation for this work grew, to a large extent, out of a day of fruitful discussions with Dr. Ralph G. Allen and Mr. Thomas J. White of Technology Incorporated.


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APPENDIX

The mathematical model for heating and thermal conduction in the retina is as follows:

1. Heat is accumulated through the absorption of light, only within a volume bounded by the intersections of (1) a right circular cylinder of radius $R_0$, and (2) a pair of adjoining parallel slabs, representing the pigmented epithelium ($0 \le z \le z_1$), and the choroid ($z_1 \le z \le z_2$). (The z axis is the axis of the cylinder).
2. Absorption of light is uniform in the radial direction within cylinder ($0 \le r \le R$ ). Along the axial direction it varies in a manner described by the familiar Beer-Lambert law.
3. The heated volume is uniform in its thermal properties (density, specific heat, and thermal conductivity), and is imbedded in an infinite medium with the same thermal properties.

Thus formally we have the initial value problem:

For all $t > 0$, for all $r > 0$, and for $-\infty < z < \infty$, $\theta_t = K \nabla^2 \theta + Q(r,z)$ such that $\theta(r,z,t=0) \equiv 0$ and such that for a unit flux at the surface of the retina,

$$Q(r_1 z) = \begin{cases} \alpha_1 e^{-\alpha_1 z}, \text{ if } z \in [0,z_1] \text{ and } r \in [0,R_0] \\ \text{and} \\ \alpha_2 e^{-\alpha_1 z_1} e^{-\alpha_2 (z-z_1)}, \text{ if } z \in [z_1,z_2] \text{ and } r \in [0,R_0] \\ \text{and} \\ 0, \text{ if } z \notin [0,z_2] \text{ or } r \notin [0,R_0], \end{cases}$$

where $0 < z_1 < z_2$ and $0 < R_0$. The general solution to the problem is

$$\theta(r,z,t) = \frac{\pi}{4(\pi K)^{3/2}} \int_0^{z_2} dz' \int_0^{R_0} Q(r',z')r'dr' \int_0^t I_0\left(\frac{rr'}{2K\tau}\right) \cdot \exp\left\{ -\frac{r^2 + (r')^2 + (z-z')^2}{4K\tau} \right\} \frac{d\tau}{\tau^{3/2}}$$

where $I_0$ is a modified Bessel function. This solution is found by using the "method of sources"[14] or by Fourier transforms.[15,16]

Since we are interested in the maximum temperature rise, we evaluate the solution on the z-axis. Letting $\theta_0(z,t) = \theta(r=0,z,t)$ we have

$$\theta_0(z,t) = \frac{1}{2} \int_0^t \left\{1 - e^{-\frac{R_0^2}{4K\tau}}\right\} \left\{ g_1(z)\, e^{\alpha_1^2 K\tau} \cdot \left[\mathrm{erf}\left(\frac{z_1-z}{2\sqrt{K\tau}} + \alpha_1\sqrt{K\tau}\right) - \mathrm{erf}\left(\frac{-z}{2\sqrt{K\tau}} + \alpha_1\sqrt{K\tau}\right)\right] + g_2(z)\, e^{\alpha_2^2 K\tau} \cdot \left[\mathrm{erf}\left(\frac{z_2-z}{2\sqrt{K\tau}} + \alpha_2\sqrt{K\tau}\right) - \mathrm{erf}\left(\frac{z_1-z}{2\sqrt{K\tau}} + \alpha_2\sqrt{K\tau}\right)\right] \right\} d\tau$$

where $g_1(z) = \alpha_1 e^{-\alpha_1 z}$ and

$$g_2(z) = \alpha_2\, e^{-(\alpha_1-\alpha_2)z_1}\, e^{-\alpha_2 z} \quad .$$

The integral is easily evaluated numerically.

As one check on the time-dependent numerical integration, we may obtain the solution to the equilibrium heating problem by taking the limit as $t \to \infty$. This solution is $\theta_0(z,\infty) =$

$$\frac{1}{2K} \int_0^{z_2} Q(z') \left\{[R_0^2 + (z-z')^2]^{1/2} - |z-z'| \right\} dz' \; .$$

The integral was evaluated numerically and compared with the numerical evaluation of the time-dependent solution at t = 1000 sec. Agreement between the two was within 0.3%.

Figure A-1 shows the temperature rise along the z-axis at various times, and at equilibrium, for the case $R_0 = 0.01$ cm, $\alpha_1 = 314$, and $\alpha_2 = 45$. The source intensity is scaled so that at equilibrium the maximum temperature rise is 20°C.

The above solutions correspond to heating by absorption of monochromatic light, wavelength $\lambda$, with absorption coefficients $\alpha_1(\lambda)$ and $\alpha_2(\lambda)$. Let us denote these solutions by $\theta_0(z,t;\lambda)$.

In order to calculate the temperature rise, $\theta_0(z,t)$, that results from the absorption of light of a given non-monochromatic spectral distribution, $A(\lambda)$, it is necessary to form a linear combination of such solutions; thus

$$\theta_0(z,t) = \int A(\lambda')\,\theta_0(z,t;\lambda')\, d\lambda' \; .$$

We define $A(\lambda)$ as follows:

$$A(\lambda) = \frac{B(\lambda)\; T(\lambda)}{\int_{400}^{1300} B(\lambda')\; T(\lambda')\; d\lambda'}$$

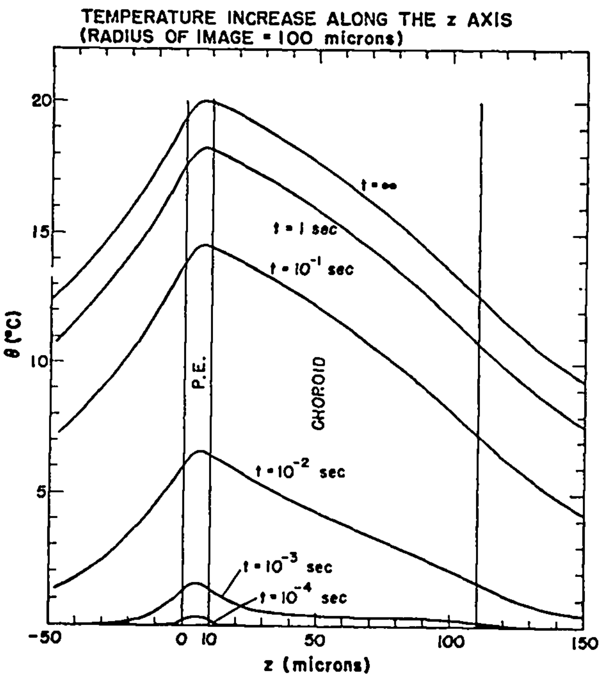


Fig. A-1. Time-evolution of axial temperature profiles for a nominal case with $R_0 = .01$ cm.

the cornea per unit wavelength interval and $T(\lambda)$ is the transmission of the ocular media. $\lambda$ is in units of nanometers. We evaluate $A(\lambda_i)$ and $\theta_0(z,t;\lambda_i)$ for 13 values of $\lambda_i$, i.e., $\lambda_i$ = 400, 450, 500, 600, 700, 800, 900, 950, 1000, 1100, 1200, 1250, 1300, nm and estimate the integral

$$\theta_0(z,t) = \int_{400}^{1300} A(\lambda') \ \theta_0(z,t;\lambda')d\lambda'$$

by the trapezoid rule.

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